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Silver and lead mineralogy in gossan-type deposits of Sierra de Cartagena, southeast Spain

J. A. López García, R. Lunar and R. Oyarzun

The strata-bound Pb–Zn–Ag deposits of Sierra de Cartagena, Murcia province, southeast Spain (Fig. 1), have been intermittently exploited since Roman times—first for silver and, in modern times, for lead, zinc and silver. These deposits are currently being worked in open-pit operations by the Sociedad Minera y Metalúrgica Peñarroya–España. Production in 1986 was 34 989 t Pb concentrate, 58 078 t Zn concentrate and 25 000 kg Ag.

Silver mineralization in gossan-type deposits has presented a major mineralogical and metallurgical problem since Roman times. The Romans were probably the best prospectors and metallurgists of classical times and knew how to exploit Ag-bearing jarosite-type minerals in the gossans of the Iberian Pyrite Belt; furthermore, they may have used jarosite-type minerals as a guide to the richest Ag horizons in the ore deposits. Indeed, they searched for the lower contact of the gossans (as shown by the most important Roman workings), where silver becomes concentrated in the form of Ag-jarosite and other oxide minerals.[1]

Today, classical—some may even say old-fashioned—studies of gossan mineralogy and textures are of major relevance to the extraction of precious metals from these and similar oxide ore deposits in that a knowledge of the ore mineralogy is essential in planning a heap-leach operation. Heap leaching is now used to treat Au–Ag bearing gossans at Tharsis, Huelva province, Spain (reserves exceed 5 000 000 t of tailings and *in-situ* gossan ore grading 1.8 g/t Au and 37.6 g/t Ag[2]), and at Grantsville, Nevada, U.S.A., where the open-pit operation has reserves of 800 000 t of gossan ore grading 4.3 oz/t silver.[3]

The Sierra de Cartagena orebodies exhibit distinct gossan-type oxidation zones, which are locally enriched in lead and/or silver relative to the primary ores. Ore grades and the Pb- and Ag-bearing minerals in the oxide zones at San Valentin and El Estrecho (Fig. 1) were studied as part of a preliminary evaluation of the supergene orebodies, which constitute reserves of 15 000 000 t. Since magnetic separation has been considered as a commercial method for the preconcentration of silver minerals from oxide ore, the method was used in the present study to effect separations from a 0.10- to 0.12-mm size fraction. Three different magnetic fractions were obtained: non-magnetic (0.5 A); intermediate (0.5–0.3 A); and magnetic (0.3 A). The test samples obtained in this way were chemically analysed by atomic absorption spectrophotometry to determine the distribution of Pb and Ag between the different fractions.

Geology

The ore deposits of Sierra de Cartagena have been studied by several authors.[4–9] Geologically, the deposits are located in the internal zone (Betic Zone) of the Betic Cordilleras; this

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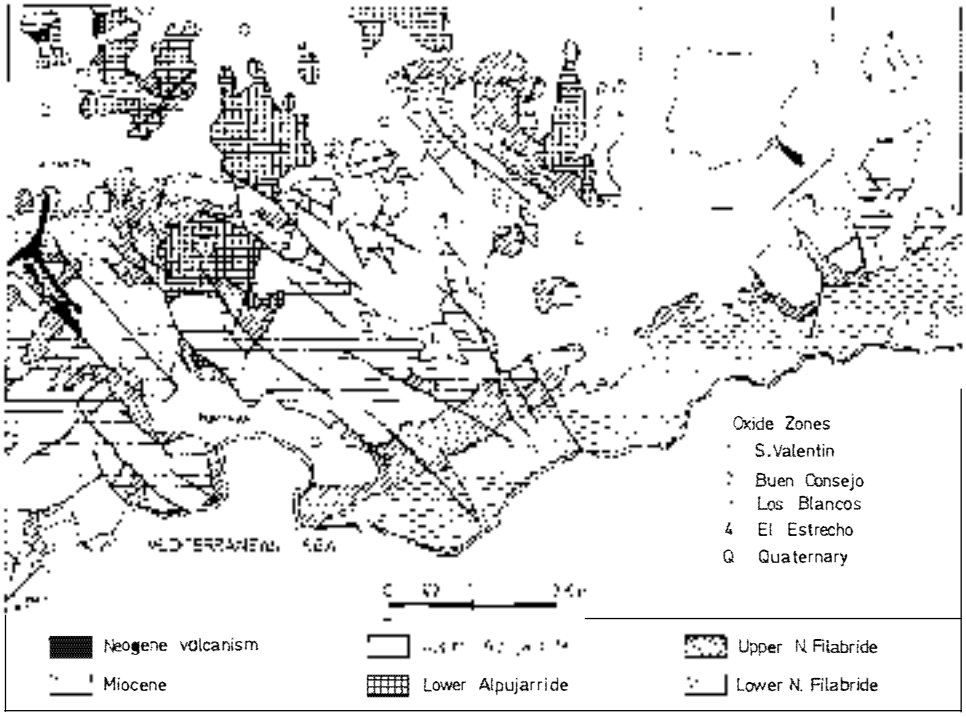


Fig. 1 Geological map of Sierra de Cartagena, Murcia, Spain (after Ovejero and [illegible])

zone is characterized by a superposition of Alpine type nappe structures in which the metamorphic grade increases from the base to the top. Two tectono-stratigraphic complexes are recognized in the area: the Nevado-Filabride Complex and the Alpujarride Complex[1] (Figs. 1 and 2). The complexes are divided into several units (Fig. 2) whose ages range from Palaeozoic (Lower Nevado-Filabride) to Permo-Triassic and Triassic (Upper Nevado-Filabride and Alpujarride respectively).

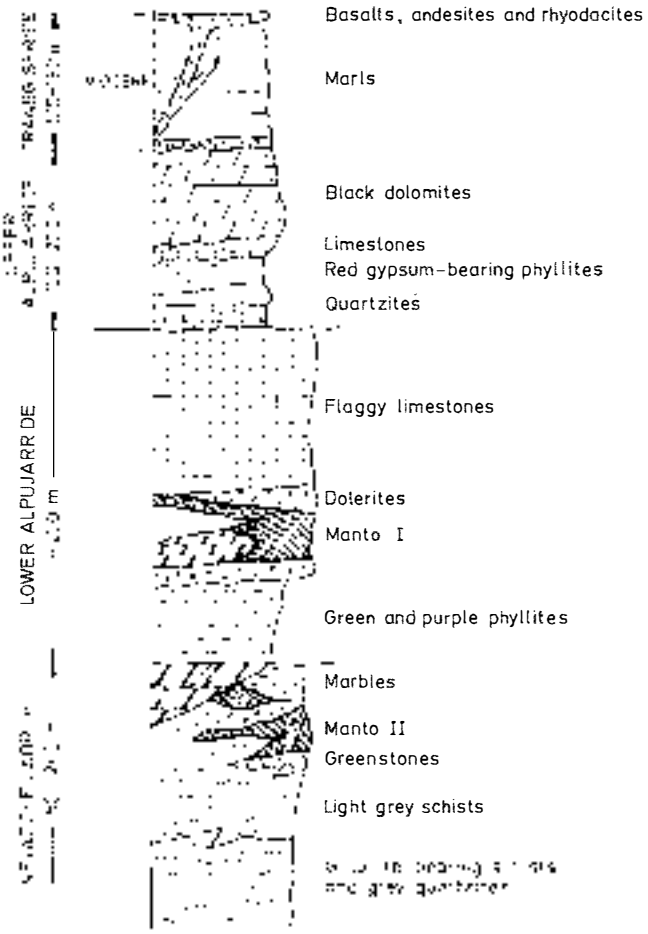


Fig. 2 Simplified stratigraphic column for Sierra de Cartagena area (courtesy of geology department, S. M. M. Peñarroya–España)

The principal ore deposits of the area are of the massive strata-bound type, the local term for which is 'mantos'. Two generations of mantos are recognized in the area.[8] The first (Manto I) is located within the base of a carbonate rock sequence of the Lower Alpujarride unit and is spatially related to dolerite bodies that belong to the same unit. The second (Manto II) was emplaced in the Upper Nevado-Filabride unit and is also spatially related to basic rocks (Fig. 2). The mantos underwent strong supergene alteration, which resulted in the formation of significant oxide zones.[7,12]

Mineralogy

Primary ores

Two types of mineralogical association are observed in the mantos: greenalite–magnetite–carbonate–sulphide–silica (assemblage (1) and sulphide–carbonate–silica (assemblage (2)). Both types are present in Mantos I and II.[7] The sulphides in assemblage (1) are pyrite, sphalerite, galena, marcasite, tetrahedrite and stannite disseminated in a matrix of greenalite. Assemblage (2) contains pyrite, pyrrhotite, marcasite, galena and sphalerite as the principal sulphides. Minor amounts of chalcopyrite, arsenopyrite, tetrahedrite, and stannite are also present. In both assemblages the carbonate is siderite with varying degrees of substitution by Zn and Mn.

The silver bearing minerals are galena (up to 3 wt% Ag) and tetrahedrite (up to 20 wt% Ag). Grades in the primary mineralization are 1 wt% Pb, 1.5 wt% Zn and 15 g/t Ag.

Gossans

The gossans of Sierra de Cartagena are the result of the supergene alteration of primary assemblages (1) and (2) to form two distinct oxide horizons. The most important ore

Table 1 San Valentin gossan ore, horizon 1.—Pb and Ag grades of core samples and associated magnetic fractions

	Total sample		Non-magnetic fraction		Intermediate fraction		Magnetic fraction	
	Pb, wt%	Ag, g/t	Pb, wt%	Ag, g/t	Pb, wt%	Ag, g/t	Pb, wt%	Ag, g/t
DDH 923								
10.0–12.5 m	4.70	30	7.35	74	2.30	25	1.44	19
12.5–15.0 m	1.85	30	1.94	30	0.98	23	1.37	50
15.0–17.5 m	1.60	44	1.05	58	1.48	4	2.84	5
17.5–19.3 m	2.15	68	0.90	145	2.00	17	2.25	20
19.3–21.8 m	1.57	62	1.02	85	2.65	30	2.50	63
21.8–22.8 m	1.32	45	0.75	185	2.65	23	2.35	22
DDH 931								
5.0–7.75 m	2.17	15	6.60	60	2.92	18	0.68	15
7.75–10.2 m	1.24	80	0.35	36	1.43	91	1.71	73
10.2–13.1 m	0.55	39	0.70	38	0.72	14	1.06	45

Table 2 San Valentin gossan, horizon (1)—main ore minerals in magnetic fractions (cores as Table 1)

Fraction	Pb DDH 923	DDH 931	Ag DDH 923 and DDH 931
Non-magnetic	Anglesite (−)	Cerussite , anglesite (−)	Cerargyrite (+), native silver (−)
Intermediate	Anglesite . Pb-coronadite	Pb-coronadite , cerussite (−)	Cerargyrite (−), native silver (−)
Magnetic	Pb-coronadite (+)	Pb-coronadite	Cerargyrite (. native silver (−)

Proportion in fraction: +, major; ±, moderate; −, minor.

Table 3 El Estrecho gossan ore, horizon (2)—Pb and Ag grades of samples and associated magnetic fractions

	Total sample		Non-magnetic fraction		Intermediate fraction		Magnetic fraction	
	Pb, wt%	Ag, g/t	Pb, wt%	Ag, g/t	Pb, wt%	Ag, g/t	Pb, wt%	Ag, g/t
1	1.15	5	0.09	6	0.83	6	1.25	6
2	2.64	10	0.38	4	2.69	15	2.49	9
3	0.97	2	0.28	2	0.86	5	1.75	6
4	0.89	4	0.05	2	0.58	10	1.05	5
5	5.52	62	0.27	6	7.95	84	5.01	78
6	2.24	35	0.20	4	4.24	72	2.36	40
7	0.37	5	0.05	2	0.27	8	0.38	8
8	1.05	4	0.08	2	0.42	4	1.04	3
9	0.60	10	0.07	4	0.43	6	0.73	8
10	0.67	7	0.02	2	1.68	18	1.09	14

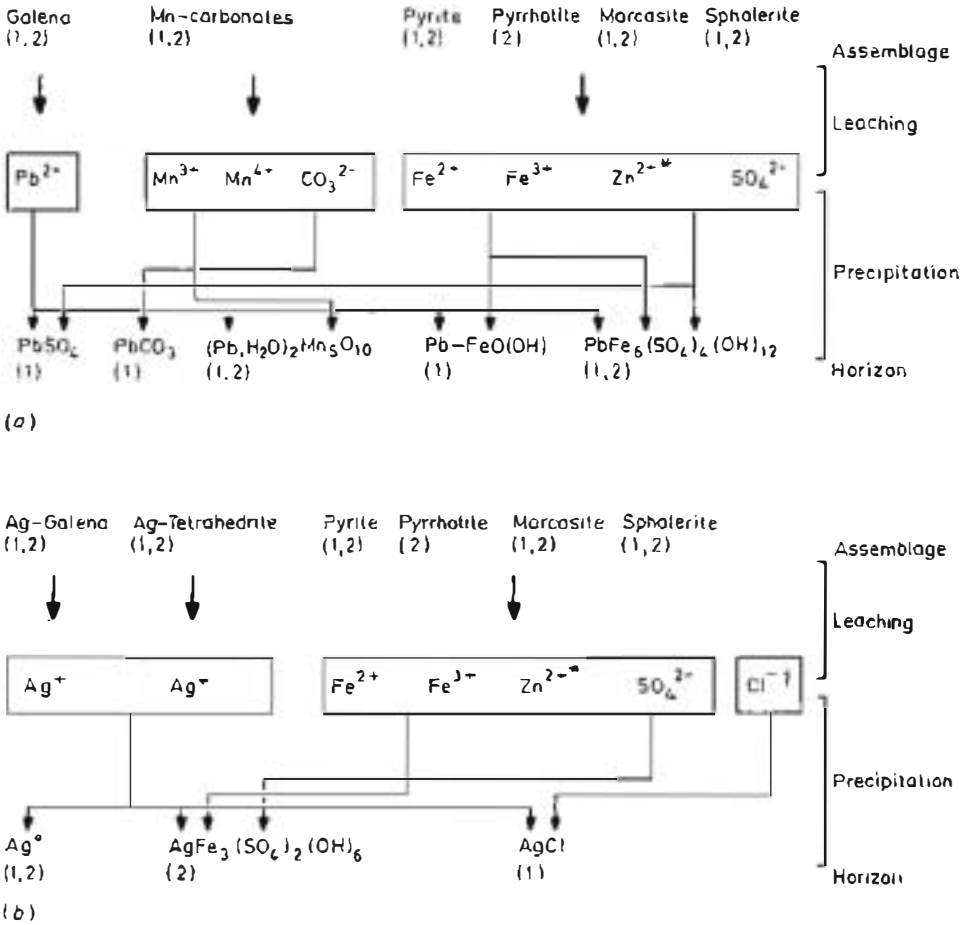
Table 4 El Estrecho gossan, horizon 2—main ore minerals in magnetic fractions

Fraction	Pb	Ag
Non-magnetic	Anglesite (−)	Native silver (−)
Intermediate	Pb-coronadite (±), Pb-jarosite (−)	Native silver (±), jarosite (−)
Magnetic	Pb-coronadite (±), Pb-jarosite	Native silver (±), jarosite (−)

Proportion in fraction: +, major; ±, moderate; −, minor.

metals present in the gossans are lead and silver. These were leached from the primary ores and precipitated as sulphates (Pb- and Ag-bearing jarosites, and anglesite), carbonates (cerussite), oxides (Pb-bearing coronadite and plumbite), native silver and halides (cerargyrite). A simplified diagram of the processes responsible for the formation of these minerals in the Cartagena gossans is presented as Fig. 3. Ore grades and mineralogy are displayed in Tables 1–4, and some textural features of the ores are shown in Figs. 4 and 5.

The mineralogical and textural characteristics of the oxide horizons developed from assemblages (1) and (2) are different. Whereas in horizon (1) derived from assemblage (1) silver occurs mainly as cerargyrite and native metal, in horizon (2) it occurs principally in jarosite and as native silver disseminated in goethite. The lead-bearing minerals are also different: anglesite, cerussite, Mn oxides and goethite in horizon (1); and Mn oxides and jarosite in horizon (2). Moreover, ore textures differ from one horizon to the other—for example, pseudomorphic textures are frequently observed in horizon (1) (Fig. 4), but in horizon (2) primary textural



*Mostly dispersed by groundwater, some of initial content remaining as smithsonite.
†Wind-borne supply.

Fig. 3 Simplified schema of formation of (*a*) secondary lead and (*b*) secondary silver minerals in supergene horizons (1) and (2) from primary assemblages (1) and (2). Occurrence of galena, for example, in both assemblages (1) and (2) results in formation of $PbSO_4$ in horizon (1) or Pb-coronadite in horizons (1) and (2). Horizons (1) and (2) derived from assemblages (1) and (2), respectively

features have largely been obliterated (Fig. 5).

The preservation or loss of primary textures, as well as metal leaching, was related to the availability of iron sulphide minerals and the presence of carbonates, which controlled the acidity/alkalinity of the system. An example of this interdependence is the oxide zones derived from assemblage (2) (sulphide–carbonates–silica), where metal leaching was stronger and primary textures are infrequently observed. In assemblage (1) most of the iron is in the form of magnetite and siderite, whereas in assemblage (2) 28% of the iron forms pyrite and marcasite. The presence of these iron sulphides produced lower pH conditions (~3, as indicated by the local occurrence of jarosite), resulting in a greater development of iron and manganese oxides. The important presence of Mn oxides in the oxide horizon developed from assemblage (2) is also a consequence of the high primary content of this element in the manto carbonates, which can contain as much as 15 wt% Mn.[9]

The presence of a silver halide, such as cerargyrite, has a particular palaeo-environmental significance in that this mineral forms only under arid to semi-arid conditions[11]—a climatic condition that is also indicated by the presence of smithsonite (a mineral of minor importance in the gossans of Cartagena). A contributing factor to the formation of cerargyrite was the proximity of this area to the sea, which resulted in an important wind-borne supply of chlorine.

Conclusions

Two strata-bound Pb–Zn–Ag orebodies (mantos) are currently being worked by the Sociedad Minera y Metalúrgica Peñarroya-España in the Sierra de Cartagena, southeast Spain. Associated with the primary ores are gossan-type oxidation zones; these supergene ores, which comprise two distinct mineral associations that were formed from the two primary manto assemblages under different pH conditions, are locally enriched in lead and/or silver.

A preliminary evaluation of the gossan ores at two of the open-pit mines was undertaken to investigate the distribution of Pb and Ag in the different magnetic fractions of the ore. The results indicate that magnetic separation as a first-stage preconcentration method after crushing could be used successfully prior to beneficiation of silver by heap leaching.

One of the factors that affect the profitability of heap leaching is the mineralogy of the ore;[14] significantly, a proportion of the silver ore mineralization
silver) at the gossans studied is amenable to heap leaching (neither mineral is a cyanicide[13]). The dryish, Mediterranean climate is ideal for heap leaching: minimum and maximum average temperatures (January and August, respectively) are 5.4° and 31°C (annual rainfall, 287 mm). Hydrometallurgical tests should indicate the level of Ag extraction that can be achieved and the optimum reagent composition and consumption rate, as well as other factors, such as crushing size,

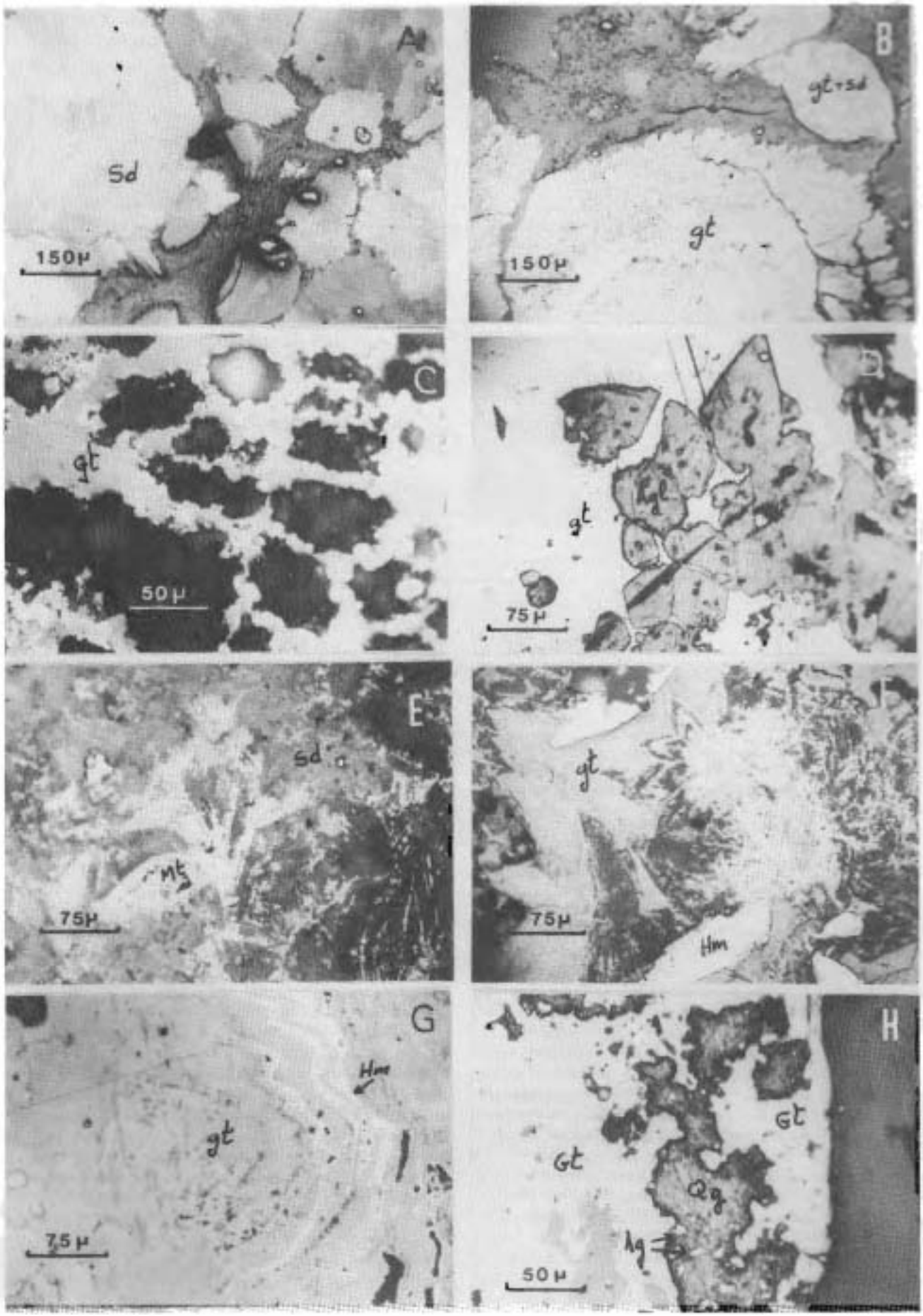


Fig. 4 Supergene horizon (1)---reflected-light photomicrographs of minerals and textures. (*A*) Roseate siderite (*Sd*); (*B*) roseate siderite (*Sd*) showing different stages of alteration to goethite (*gt*); (*C*) goethite (*gt*) replica texture after galena; (*D*) crystals of anglesite (*Agl*) intergrown with goethite (*gt*); (*E*) intergrowth of magnetite (*Mt*) and siderite (*Sd*); (*F*) hematite crystals (*Hm*) with goethite (*gt*) pseudomorphs after siderite; (*G*) hematite (*Hm*) and goethite (*gt*) preserving original banding of magnetite–siderite; (*H*) cerargyrite (*Qg*) crystals with inclusions of native silver (*Ag*) and intergrown with goethite (*Gt*)

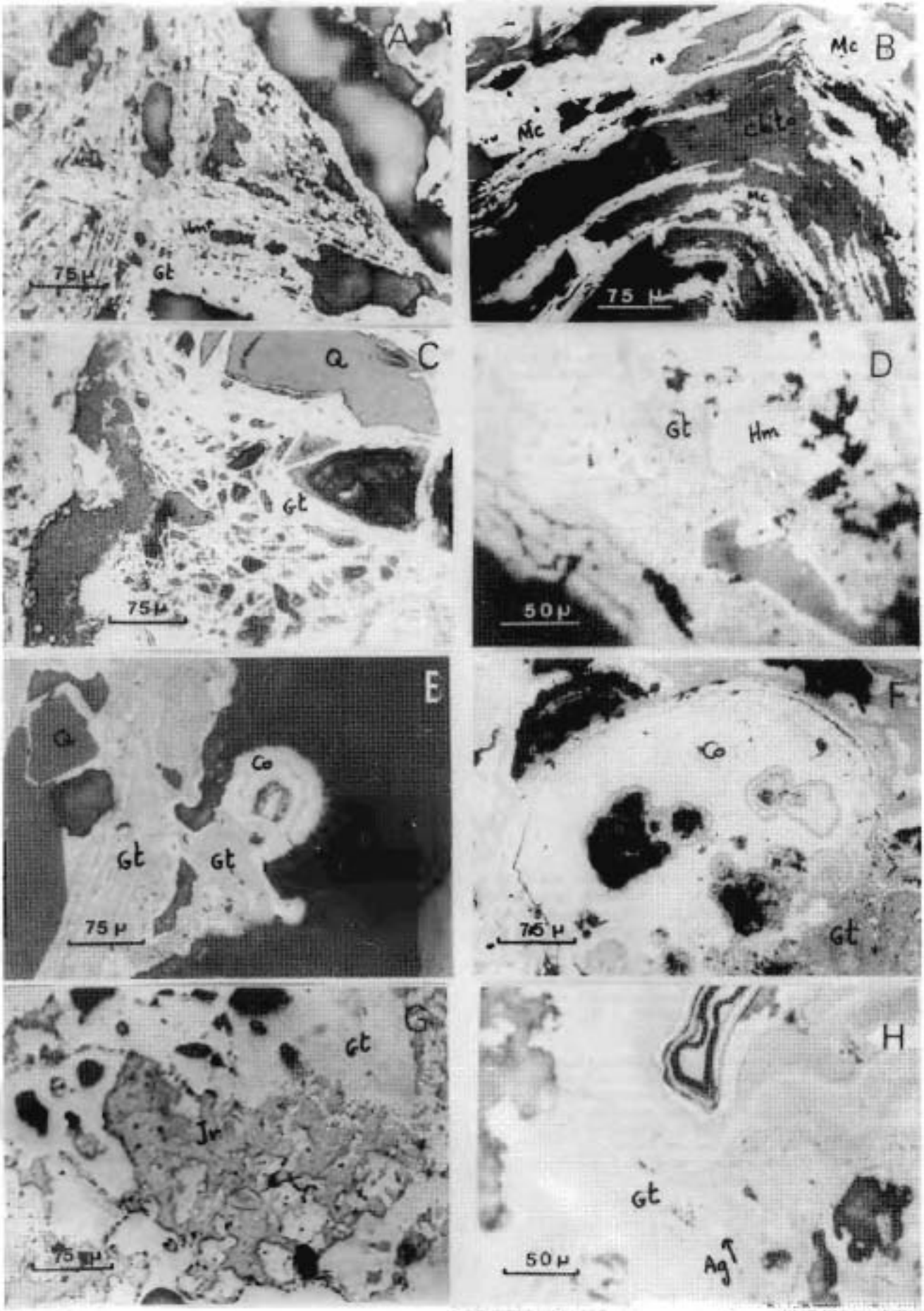


Fig. 5 Supergene horizon (2)—**reflected-light photomicrographs of minerals and textures.** (*A*) Banded hematite (*Hm*) and goethite (*Gt*) after marcasite; (*B*) banded texture of **marcasite** (*Mc*) **and carbonates** (*Cbto*); (*C*) goethite (*Gt*) replica textures after sphalerite; (*D*) goethite (*Gt*) pseudomorphs after siderite; (*Hm*) **hematite;** (*E*) **coronadite** (*Co*) and goethite (*Gt*) pseudomorphs after marcasite; (*F*) colloidal textures of coronadite (*Co*) and goethite (*Gt*); (*G*) **jarosite** (*Jr*) **infilling voids in goethite** (*Gt*); (*H*) colloidal textures of goethite (*Gt*) and disseminated native silver (*Ag*)

amount of solution needed to saturate the ore, etc. Before any major investment, however, careful consideration will have to be given to the rather low grades of silver (≤80 g/t in bulk samples and 185 g/t in magnetically separated ore) and to the depressed market price of the metal.

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New evidence of epithermal gold potential in andesitic volcanics of the Central Inlier, Jamaica

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Detrital native gold of high fineness is reported in drainage samples from the Mountain River at Cudjoe Hill on the southeast margin of the Central Inlier, St. Catherine Parish, Jamaica (Fig. 1). The gold is associated with volcano-sedimentary sequences of andesitic affinities and with anomalous geochemical haloes for As and Ag, which are indicative of epithermal gold mineralization.[1–3] The volcanic pile has been locally intruded by Cretaceous granodiorite at Ginger Ridge, 2.5 km southwest of Juan de Bolas mountain (Fig. 1).[8]

The Caribbean plate is a favourable area for gold exploration and, by analogy with the present western Pacific plate margin, has potential for epithermal deposits related to volcanic hot springs at crustal plate boundaries.[4] Jamaica has no record of gold mining, though Sawkins[13] recognized the gold potential of mineralization in the Stamford Hill, Charing Cross and Golden Mine localities in northeast Clarendon[5,10] to the west of the present study area, which he classified as gold ore.

Geochemistry

Gold was observed in pan concentrates where the Mountain River emerges from a gorge in the Troy facies of the Troy–Claremont Formation (site (10), Fig. 1). Field examination of andesitic volcanics of the Central Inlier (site (2), Fig. 1) indicated the presence of finely disseminated pyrite in the Arthur's Seat Formation and Eastern Volcanic Group, which may, therefore, be a primary source of gold.

Thirteen pan concentrate samples were analysed by X-ray fluorescence (XRF) for 28 elements, including the gold pathfinder elements As and Ag, which indicated the presence of a geochemical halo. The highest arsenic values coincide with the presence of sulphides in bedrock (50 ppm As at site (2), Fig. 1), and the highest silver values tend to reflect sites favourable for the accumulation of detrital gold, such as the Mountain River gorge (5–11 ppm Ag), drainage samples from locations underlain by the Guy's Hill Member of the Yellow Limestone Group (9 ppm Ag) and the alluvium near Lloyds (11 ppm Ag) (Fig. 1). The ranges for other indicator elements are, ppm: Ba, 45–1034; Zn, 217–535; Sb, 0–9; Cu, 53–231; and Mo, 4–9. The higher values are anomalous and are also indicative of epigenetic mineralization.

Geology

The geological setting for gold in the Mountain River catchment basin is dominated by andesitic volcanics of the Arthur's Seat Formation and Eastern Volcanic Group. They represent the oldest of the major Cretaceous subdivisions of the Central Inlier (Fig. 1).[9]

The Arthur's Seat Formation consists of poorly bedded, unsorted epiclastic volcanic conglomerates and breccias, together with subordinate laminated volcanic grits, sand-

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